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## QUASI-ELASTIC AND DEEP-INELASTIC PRIMARY CROSS SECTIONS IN THE $^{20}\text{Ne} + ^{159}\text{Tb}$ REACTION AT 15 MeV/u

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The  $^{20}\text{Ne} + ^{159}\text{Tb}$  reaction was studied at  $E_{\text{lab}} = 294$  MeV with the KX-ray method. Partial cross sections  $d\sigma(Z_{\text{PLF}}, Z_{\text{TLF}})/d\Omega_{\text{PLF}}$  were obtained for the quasi-elastic as well as the deep-inelastic components. Primary projectile-like fragment cross sections were reconstructed for both components and the corresponding probabilities for sequential charged particle decay of the fragments were deduced. These probabilities are used to extract information about the excitation energy of the primary fragments.

A characteristic feature of heavy ion reactions is their increasing complexity with bombarding energy, as the number of reaction channels increases while the products themselves become particle unstable. For a quantitative understanding it therefore is of prime importance to identify the individual channels and to deduce the cross section of the unstable fragments prior to their decay. In a systematic investigation of  $^{14}\text{N} + ^{159}\text{Tb}$  reactions with the KX-ray method between 6 and 23 MeV/u the evolution of the reaction mechanism was studied [1]. Here we report on a complementary investigation of  $^{20}\text{Ne} + ^{159}\text{Tb}$  at 15 MeV/u in which, in contrast to the  $^{14}\text{N} + ^{159}\text{Tb}$  system, a clearly identifiable deep-inelastic (DI) reaction component is observed in addition to the quasi-elastic (QE) component even at angles close to grazing [2]. We find a distinct difference between the decay pattern of QE and DI fragments. Whereas QE projectile-like fragments (PLF's) are still found in particle stable states, this is not so for DI fragments. A preliminary account of the present work has been published in conference proceedings [3], while a complete presentation of the results together with the

experimental details and a comparison with theoretical predictions will be published in a forthcoming paper [4].

The experimental method that involves the measurement of coincidences between PLF's and characteristic KX-rays from TLF's has been discussed extensively before [1,5]. A metallic  $3.9 \text{ mg/cm}^2$   $^{159}\text{Tb}$  target was bombarded with a  $^{20}\text{Ne}$  294 MeV beam from the KVI cyclotron. Projectile-like fragments were detected in Si-detector telescopes placed at  $20^\circ$ ,  $25^\circ$ ,  $65^\circ$  and  $137^\circ$ . Here we will present data for the telescope at  $25^\circ$  only. A  $16 \text{ mm}^2$  ( $2 \text{ cm}^3$ ) Ge detector was used to measure the KX-rays. It was placed at an angle of  $75^\circ$  and at a distance of 6 cm from the target. In order to reduce the intensity of the LX-rays a 2 mm thick Al absorber was placed in front of it. Eleven plastic scintillator phoswich detectors [6] were placed at backward angles to measure charged particles evaporated from the target-like fragments (TLF's). Together these detectors covered a solid angle of 3 sr. Coincidences were measured between the PLF's and the KX-rays of the TLF's, in addition light charged particles detected by the phoswich detectors were recorded.

The characteristic KX-rays from the TLF together with the atomic number of the PLF's obtained from

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the Si-telescope permits the determination of the missing charge  $\Delta Z$

$$\Delta Z = Z_{\text{PROJ}} + Z_{\text{TARG}} - Z_{\text{PLF}} - Z_{\text{TLF}}.$$

It is then possible to determine whether the reaction is "charge binary" ( $\Delta Z=0$ ), or whether in addition to the detected PLF other charged particles have been emitted. This is shown in fig. 1 in which KX-ray

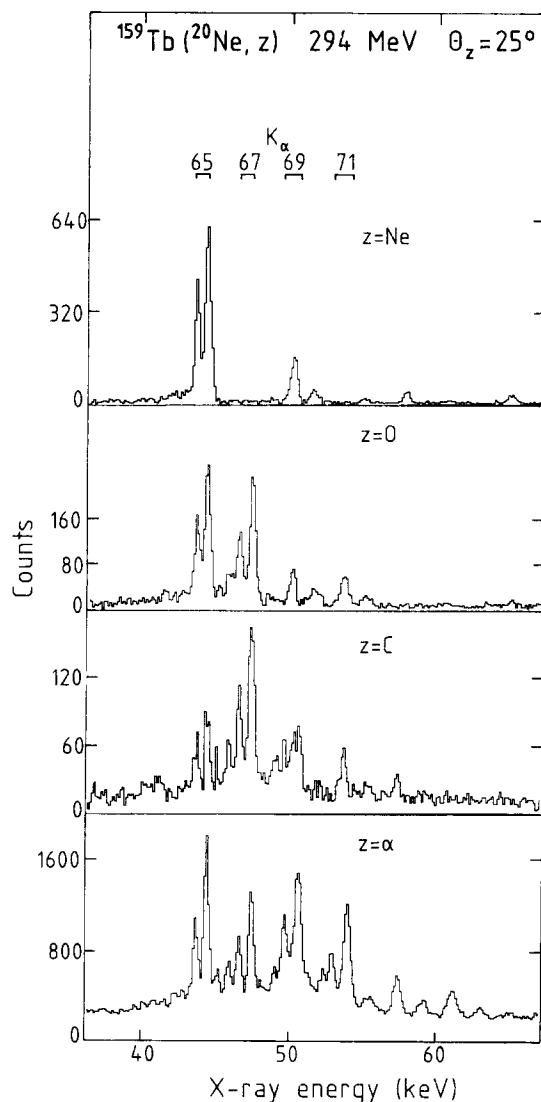


Fig. 1. Energy spectra of KX-rays from the  $^{20}\text{Ne} + ^{159}\text{Tb}$  reaction detected in coincidence with various PLF's. The  $K_\alpha$  peaks of the odd  $Z$  residues are indicated, Tb has  $Z=65$ .

spectra measured in coincidence with neon, oxygen, carbon and alpha particles are presented. These spectra clearly show the main features of the reaction. In addition to the KX-rays associated with charge-binary reactions a strong contribution of non-binary reactions is observed in the X-ray spectra gated on PLF's lighter than neon. From particle-particle correlation measurements it is known that sequential decay is important in these heavy ion reactions [7-9]. The X-ray spectrum gated on carbon particles shows for example the possibility that a primary neon ejectile can decay to carbon by the emission of two  $\alpha$  particles.

With a knowledge of the KX-ray multiplicities partial cross sections  $d\sigma(Z_{\text{PLF}}, Z_{\text{TLF}})/d\Omega_{\text{PLF}}$  can be determined. In the previous study of the  $^{14}\text{N} + ^{159}\text{Tb}$  reaction [1] it was found that this can be done reliably by employing the same average X-ray multiplicities of 0.6 for  $Z_{\text{TLF}}$  even and of 1.2 for  $Z_{\text{TLF}}$  odd. The sum of the partial cross sections should give the inclusive cross sections, i.e.

$$\left(\frac{d\sigma(Z_{\text{PLF}})}{d\Omega}\right)_{\text{INCL}} = \sum_{\text{TLF}} \frac{d\sigma(Z_{\text{PLF}}, Z_{\text{TLF}})}{d\Omega_{\text{PLF}}}.$$

In the present experiment this balance is observed with an accuracy of about 20%. The missing charge ( $\Delta Z$ ) includes charged particles evaporated from the TLF following the primary reaction. To determine such a contribution, triple coincidences were measured between the PLF detected at forward angles, the evaporated particle detected in the phoswich array at back angles, and the KX-rays. For every reaction channel the average amount of TLF evaporation was then used to obtain the primary TLF charge distributions. The results presented in the following all have been corrected in this way for charged particle evaporation from the TLF. These corrections amount to less than 1 mb/sr for  $Z_{\text{PLF}} > 3$ .

From the balance of the partial cross sections for the same  $Z_{\text{TLF}}$  and with the assumption of sequential decay, the primary cross sections and the corresponding decay probabilities can be determined. Hereby kinematical effects are neglected, i.e. it is assumed that on average the detected PLF is emitted in the same direction as the primary fragment, this is approximately the case for sequential decay.

The particle energy spectra for PLF's with  $Z \geq 6$

(not shown) all exhibit a pronounced quasi-elastic and a deep-inelastic component even close to the grazing angle. The partial cross sections correspondingly have been divided into a QE and DI component. For the light PLF's the division was obtained by extrapolating the  $Z$ -dependence of the minimum in the kinetic energy spectra. Assuming sequential decay, as discussed above, to be the origin of the missing charge, the partial cross sections are plotted for different primary fragments ranging from carbon to neon as indicated in fig. 2. Whereas the QE component peaks always at  $\Delta Z=0$ , this is not the case for the DI component. Fig. 2 clearly indicates that most of the primary DI fragments do not survive but decay via charged particle emission. Alternatively, a light charged particle might have been emitted first in an early stage of the reaction with the remainder of the projectile subsequently undergoing a DI collision [10,11]. In the present experiment these two processes cannot be distinguished.

The sequential decay probability of QE PLF's has also been deduced for the system  $^{20}\text{Ne} + ^{197}\text{Au}$  [12,13] at similar energies but using different methods. These methods did not allow one to identify the decay by proton emission but given this limitation the results from these measurements agree very well with ours.

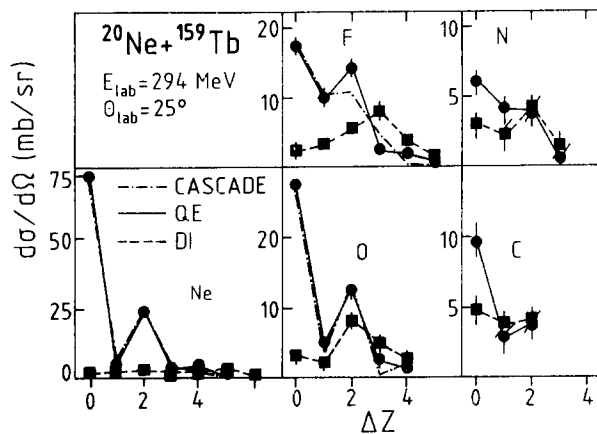


Fig. 2. Partial cross sections as a function of missing charge  $\Delta Z$  for various primary PLF's divided into quasi-elastic (QE, dots connected by full line) and deep-inelastic (DI, squares connected by dashed line) components. For the QE component of Ne, F and O the result of an evaporation calculation is shown (dash-dotted line) described in the text.

In the following we make use of the characteristic and distinct dependence of the partial cross sections on the missing charge (i.e. on the sequential decay chains) to extract information about the excitation energy of the primary fragments. Shown in fig. 2 as a dash-dotted curve is the result of a CASCADE [14] statistical model calculation for the QE component for  $^{20}\text{Ne}$ ,  $^{19}\text{F}$  and  $^{18}\text{F}$  (50% each) and  $^{16}\text{O}$  as primary fragments in which an exponential excitation energy distribution in the primary fragment of the form

$$P(E^*) = (1/\varepsilon) \exp(-E^*/\varepsilon)$$

was used. Such an exponential distribution of the excitation energy has been observed in particle correlation experiments [15,9,16]. Also depending on the assumed isotope distribution, the slope parameters  $\varepsilon$  are found to range between 7.5 and 10 MeV. The exponential dependence shows that in QE reactions the PLF is relatively cold as compared to the excitation of the TLF. Note that in the reaction  $^{16}\text{O} + ^{197}\text{Au}$  at 32.5 MeV/nucleon a similar slope parameter of about 10 MeV has been observed (fig. 2 of ref. [16]).

For DI reactions the partial cross sections show a quite different behaviour. Whether assuming the  $Z/A$  of the primary ejectile to be that of the composite system or that of the projectile, the evaporation calculation requires a mean energy of the PLF that is much larger than expected on the basis of equal temperatures for the PLF and TLF. For example, for oxygen ejectiles the average excitation energy needed is 60–80 MeV with a FWHM of about 40 MeV, while thermal equilibrium only leads to 20 MeV excitation energy. The high excitation energies required for the statistical model calculations might be an indication for the importance of non-binary DI inelastic processes, e.g. incomplete deep-inelastic collisions [10,11].

In fig. 3 the same data as shown in fig. 2 are presented in a different way. Plotted are the primary cross sections at  $25^\circ$  for the emission of the PLF either in a particle stable (hatched area) or particle unstable (open area) state. The cross sections again are divided into a QE and a DI part. Since the present method is insensitive to neutron emission, the terms particle stable or unstable refer to charged particle emission only. From fig. 3 it is seen that the cross section distribution of the DI component over the different PLF's is rather flat in contrast to the QE part

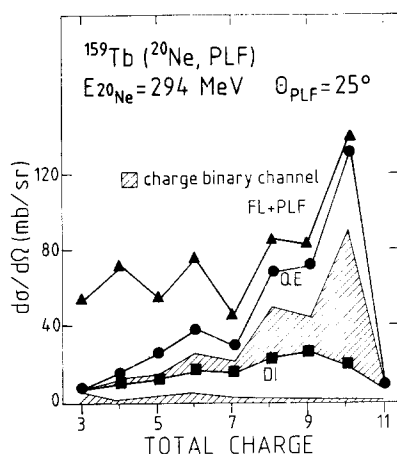


Fig. 3. Primary cross sections for PLF's (total charge) measured at  $25^\circ$ , divided over the QE, DI and fragmentation-like (FL) component. The hatched areas indicate the emission in a particle stable state.

that is peaked around the projectile. Moreover, few DI fragments are emitted in a binary reaction, the primary reaction could still be binary but also non-binary reactions may contribute, as mentioned earlier. As expected for a direct process, the primary QE cross section drops off as the PLF is further removed from the projectile, i.e. when more particles are transferred from the projectile to the target. By virtue of the method by which the non-binary cross sections have been reconstructed the QE and DI channels contain at least one PLF with  $Z \geq 3$ . Fragmentation-like (FL) channels in which the primary fragments completely disintegrate into light particles ( $Z \leq 2$ ) are therefore not included. Such processes have been identified [17,16] before and also occur in the present reaction [4]. Their contribution can be estimated on basis of the cross section balance for light particle emission and have been added for completeness in fig. 3, cf. refs. [17,1]. This fragmentation-like (FL) cross section, like the DI one, may either result from primary binary reactions or from non-binary

reactions, and the FL and DI cross sections, in fact, could be of the same origin.

With the KX-ray method partial cross sections were obtained for the  $^{20}\text{Ne} + ^{159}\text{Tb}$  reaction at 15 MeV/u. They were separated for the quasi-elastic and the deep-inelastic components. Assuming binary processes the cross section of the primary reactions were deduced. Information concerning the excitation energy of the primary projectile-like fragments was extracted, and reflect clearly the characteristic difference in the emission of QE and DI reactions. In the latter only few PLF's are emitted in a binary reaction with the DI fragment in a particle stable state.

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